Toward Printable Ubiquitous Internet of Things with Capacitive Sensing, Communications and Identification Tags

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Many types of human activities involve interactions with passive objects. Thus, by wirelessly sensing human interactions with such "things", one can infer activities at a fine resolution, enabling a new wave of ubiquitous computing applications. On the one hand, the ability to sense touch in the physical world can form the basis of the tangible user interface, which allows human to use omnipresent objects as a command-and-control interface to the digital world [13, 31, 35, 36]. On the other hand, the sequence of objects used can enable inference of human activities [25, 29]. Logs of objects touched can become the basis of "experience sampling" [6] or "life-logging" [16] that try to reconstruct a user's day. Post-processing of the logs can support many activity-aware applications, such as stroke rehabilitation assessment in homes, consumer analytics for retail stores [14, 21] *etc.*

To harvest these benefits, a practical system needs to satisfy two requirements. First, such system needs to *sense touches* on different spots of the same object, and be able to *distinguish touches* on different objects. Second, it requires to be simple, flexible and cheap enough so that users are able to fabricate them using the off-the-shield inkjet printer or paints in large scale without professional engineering skills. Although many existing sensors can detect object usages and touch interactions using heterogeneous machine learning algorithms *e.g.* motion sensors [29] and cameras [10, 15, 20], they often require augmenting the objects with batteries/circuits, or may provoke strong visual privacy concerns [7]. RFID technology can overcome such limitations by attaching energy-harvesting tags on objects. However, their antennas are typically made of metal pieces using screen printing approach and cannot be easily attach on non-flat surface of irregular objects. Beside, they are barely used in common consumers' daily life due to the high costs compared to printed barcodes [35].

This project explores the feasibility and limits of long range inkjet printable ***Cap**acitive Communications, Sensing and Identifications **Tags*** (CapTags), empowering a new paradigm of communications and sensing modality for future generation *printable* IoTs. Figure 1 in the Appendix shows our long-term vision where CapTag is a passive paper-like tag, comprised of chipless or chip-based capacitive communication/sensing components, together with printable electrodes (capacitive "antennas"). Owing to its passive nature and thin form factor, CapTag can be attached on everyday objects and even woven into clothes, thus truly advancing Weiser's vision of ubiquitous computing [37]. Our project aims to tackle two fundamental questions:

• **Design and Fabrications:** How to **design the printable capacitive-coupled tags** as well as interaction surfaces, such that any user can customize and print the tags to accommodate their own sensing/identification applications?

• **Sensing and Communication Algorithms:** How to **extend the capacitive sensing range** for both air-coupling and body-coupling communications?

To address these challenges, we will design the tag structure to ensure easy fabrication on off-the-shelf inkjet printers [4, 5] without professional skills. We propose to use *capacitive coupling* [43] as the sensing and communication method because it does not have strict requirements on the resistance and shape of antenna, meaning conductive inks having moderate resistance can be used to fabricate such antennas [11, 12, 22, 23, 35]. Based on our works on chipless passive RFID [13] and prior art in capacitive wireless power transfer [8, 18], we introduce an approach to achieve *hardware featurization* where the resonating frequencies of passive printable resonators on the tag are used to encode information that can be read remotely by an interrogator, *i.e.* reader.

To enable long range sensing with high reliability, we propose a novel sensing approach, named as *High Frequency Swept Frequency Resonating Sensing* (HF-SFRS). Unlike prior works that examine spectrum less than 5MHz [26, 38–41], CapTag's features will be sensed up to 800MHz frequencies. Evidence from high pass characteristics of capacitors and *Personal Area Network* (PAN) [17, 24, 42] supports the intuitions that higher frequency allows more displacement current passing through the coupling region, leading to long sensing range and higher reliability. Furthermore, we introduce a mixture of *closed-form* and *data-driven* approaches to identify human-tag interactions and surrounding sensings. This means the *constant resonating properties* created by resonators of CapTag can be used to mark unique touch points, while the *inconstant resonating properties* reveal the characteristics resulting from diverse surroundings and movements. This allows us to interpret the physical environment and identify human-tag interactions under the same settings.

Through preliminary feasibility study, we have proven that the resonating characteristics can be observed via capacitive coupling with frequency sweeping up to 800MHz in long spatial range. Besides tagging, we see the potentials for incorporating CapTags into scalable printable IoT infrastructures, for realizing printable human-object interaction surface, supply-chain tagging and resonating-characteristics based biometric authentications *etc.* To further motivate our vision, we marked ubiquitous interaction surfaces and mechanical buttons in our building, which can be repurposed easily into printable IoT with CapTag (see figure 2). We encourage the rich harvesting of pervasive infrastructures such as floors and furniture *etc.* as the *environmental antenna*, truly embedding the sensing and communications into ubiquitous background [37] and realizing the vision of *printable ubiquitous computing*.

*** Ke will join UC San Diego as a doctorate student in Fall 2019.**

APPENDIX
Figures and Conceptual Diagrams

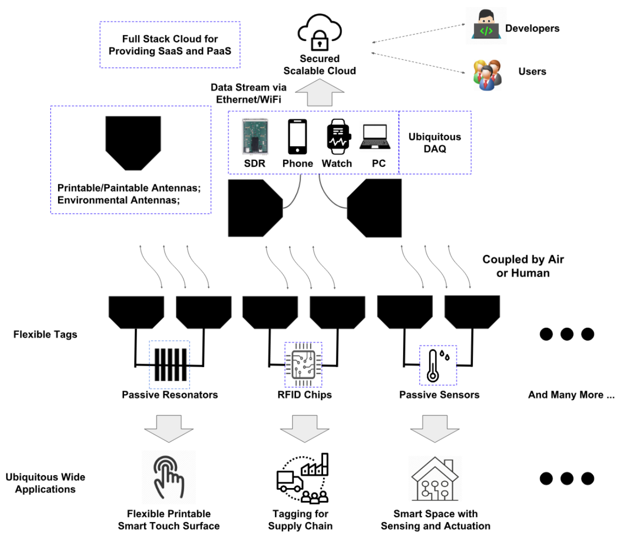

Figure 1: Conceptual diagram of *CapTags*. We envision these tags can be widely used for heterogeneous applications. For example, by combining printing antenna with discrete resonators, it is possible to create multi-touchpoints where different touch locations can be identified from resonance frequencies in spectrum. With the supports of the RFID chips and passive sensors, these tags can be widely used in supply chain and surroundings inferences in smart space [19] where data can be decoded from time-series samples. To build a printable IoT, we also propose an industrial standardized cloud, where both developers and users can utilizing the off-the-shield *Platform as a Service* (PaaS) and *Software as a Service* (SaaS).

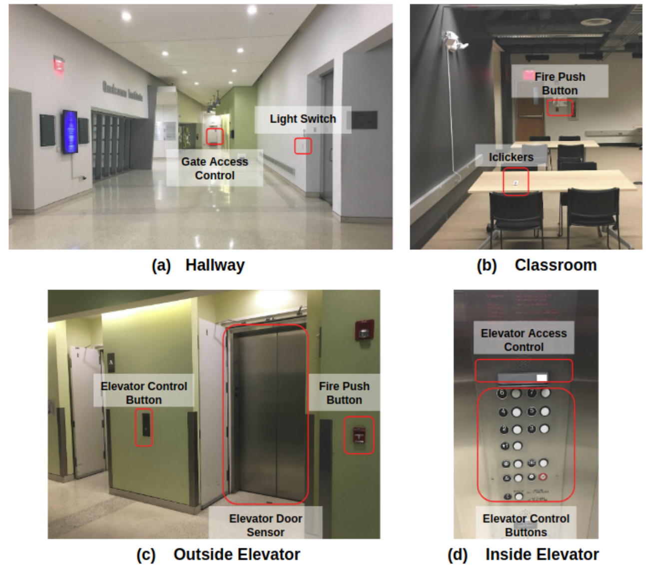

Figure 2: Ubiquitous interaction surfaces/buttons in Atkinson Hall, the Qualcomm Institute Building at UC San Diego [30]. We envision to use printable *CapTag* to replace many of these interaction surface and mechanical buttons. Note that the iClicker shown in (b) is a student remote response system, widely used in many US institutions as classroom engagement tools [1].

Research Plan

As an initial proposed plan, this project will be executed in 3 phases:

- **Phase 1: Sensing Modality Evaluations:**
  - Evaluate and benchmark the sensing modality via capacitive coupling in terms of sensing range, electrical field plate antenna size as well as the communication medium, *e.g.* air and human body *etc*;
  - Evaluate the potentially of using customized designed discrete resonators, off-the-shield RFID chips and the passive sensors to distinguish different touch points on time domain and frequency domain;
  - Performance measurements of using inkjet printing approach, *e.g.* [2] and off-the-shield paints *e.g.* [4];

  Provisional Duration: September '18 - February '19;
- **Phase 2: Sensing System Design and Prototyping:**
  - Build the reader for data acquisition and tag hardware, such that the signal can be collected reliably;
  - Investigate the optimal algorithms for detecting spikes from frequency response if discrete resonators are used and bit stream from time-series data if RFID chips are repurposed;
  - Run heterogeneous pilot user study to evaluate the performance and sensing reliability across different individuals, space and time;

  Provisional Duration: February '19 - May '19;
- **Phase 3: Toward a Ubiquitous Printable Internet of Things:**
  - Design and build a scalable backend server that is able to handle sensor stream coming from different nodes;
  - Scale out the tags and incorporating into various scenarios *e.g.* touch interface and PAN, and continue investigate the potentiality of printable ubiquitous Internet of Things;

  Provisional Duration: May '19 - December '19;

Team Members

Chen Chen is a first year Ph.D. student at the Department of Computer Science and Engineering, UC San Diego under the advisor of Prof. Xinyu Zhang. He received a Master of Science degree in Electrical and Computer Engineering from the Carnegie Mellon University (Winter 2017) and a First Class Bachelor of Engineering degree in Electrical and Electronic Engineering from the University of Nottingham, UK (Summer 2016). His research interests are broadly include mobile computing and wireless sensing for human-computer interactions. His previous research work on Mites/Synthetic Sensor under the advisors of Prof. Yuvraj Agarwal from Institute for Software Research and Prof. Christopher Harrison from Human Computer Interaction Institutes at Carnegie Mellon University was filed under US Patent [3] and is now in the process of being commercialized! For more information about him, please visit: http://cseweb.ucsd.edu/~chc004/.

Ke Sun will join the Department of Computer Science and Engineering, UC San Diego as a Ph.D. student in Fall 2019 under the advisor of Prof. Xinyu Zhang. He is currently a final year Master student advised by Prof. Wei Wang at the Department of Computer Science, Nanjing University, China. He was conferred a Bachelor of Science Degree in Computer Science from Nanjing University of Aeronautics and Astronautics, China with national Outstanding Undergraduate Award (Summer 2016). His research interests mainly include wireless sensing, mobile computing as well as human-computer interactions. As an outstanding researcher, his previous works were frequently published in several top tier conferences including ACM MobiCom 2018 [28] and 2016 [34], IMWUT (UbiComp) 2018 [32], ICPP 2018 [9], MobiSys 2018 [27], and IEEE SECON 2018 [33]. For more information about him, please visit: https://samsonsjarkal.github.io/KeSun/.

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